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GENERATION AND USE OF THE GODDARD TRAJECTORY DETERMINATION SYSTEM SLP EPHEMERIS FILES

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SLP EPHEMERIS FILES

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January 1973

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GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

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ABSTRACT

This document is intended to acquaint users of the Goddard Trajectory Determination System (GTDS) Solar/Lunar/Planetary (SLP) Ephemeris Files with the details connected with the generation and use of these files. In particular, Sections 2.2, 3 and 4, together with Appendices B through D, constitute a user's manual for the GTDS SLP Ephemeris Files.

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APPENDICES

SECTION 1

INTRODUCTION

Using a Jet Propulsion Laboratory (JPL) planetary ephemeris tape as a data source, the Goddard Trajectory Determination System (GTDS) has the capability of generating Solar/Lunar/Planetary (SLP) ephemeris files which contain data in the form of Chebyshev polynomial coefficients.

The current JPL Export Ephemeris (DE-19) contains the most accurate predictions (in terms of a long-span time interval) of lunar and planetary motion available for the time interval from December 30, 1949 to January 5, 2000. It consists of three tapes which collectively span the interval as follows:

- December 30, 1949 to December 29, 1969
- November 19, 1969 to February 22, 1984
- January 13, 1984 to January 5, 2000.

Depending upon the particular body represented, the stepsize for the ephemeris data contained on these tapes is either 1/2 day, 2 days, or 4 days. This tabular ephemeris data can be used directly via use of the JPL software which provides interpolated values of position and velocity vectors of any requested set of bodies relative to any requested central body. (A more detailed description of the JPL Ephemeris Tape System is given in Appendix A.)

However, more efficient use of the tabular data is provided by the GTDS file generation procedure by utilizing Chebyshev polynomial curve-fitting techniques and by allowing the SLP ephemeris representation of concern to be given in terms of long arc lengths in the neighborhood of a month. The corresponding degree of the polynomial fit is chosen sufficiently high so as to maintain accuracy comparable with that of the JPL data. The improved efficiency is provided in terms of reducing the computational time required for the various calculations and transformations which may be required for use by GTDS as described in Section 2.1.

SECTION 2

GTDS SLP EPHEMERIS FILE GENERATION

2.1 PURPOSE

A SLP ephemeris file in GTDS contains data in the form of Chebyshev polynomial coefficients. Use of these data (as opposed to the direct use of JPL data) reduces the computational time required for the following calculations and transformations:

a. The calculation of the positions and velocities of planetary bodies.

b. The calculation of the equation of the equinox and the A.1 to UT1 time conversion for the Greenwich Hour Angle.

c. The transformation from (or to) the mean equator and equinox of 1950.0 to (or from) a true equator and equinox system.

d. The transformation from selenocentric to selenographic coordinates.

The above calculations are required for the non-analytic orbit generators and for the calculation of observations, while the transformations may be achieved for the same purposes if the need exists. The calculations and transformations are achieved by evaluating the ephemeris polynomials. The expression for the polynomials is given by:

$$X(t) = \sum_{i=1}^{n} k_i \left(\frac{t - t_m}{86,400}\right)^{i-1} \tag{1}$$

where

$X(t)$ = the desired vector, equation, or matrix to be solved (matrices are used in transformation computations)

k_i = the ephemeris polynomial coefficients

t = the time in seconds from the beginning of the ephemeris year

t_m = the time in seconds from the beginning of the ephemeris year to the midpoint of the curve-fit interval

n = degree of the polynomial plus one

Details pertinent to the calculations and transformations given by b., c., and d. may be found in the document GODDARD TRAJECTORY DETERMINATION SUBSYSTEM MATHEMATICAL SPECIFICATIONS (March, 1972).

2.2 DISCUSSION OF GENERATION PROCEDURE

The generation of a SLP ephemeris file in GTDS is an operation performed by the Data Management Program which primarily is responsible for generating working files of data to be used immediately by other programs in the system. The Data Management Program may also operate as a stand-alone program whereby files may be created for future use. The generation of a SLP ephemeris file is initiated via the Data Management Program's testing of switches which determines the data management operations to be performed. A determination is then made as to which of the following three operations relating to SLP ephemeris file generation is to be performed:

1. Generate a SLP ephemeris tape file from a JPL ephemeris tape.

2. Generate a SLP ephemeris disk file from a JPL ephemeris tape.

3. Generate a SLP ephemeris disk file from a SLP ephemeris tape.

The creation of any one of these files is initiated through the use of the following SLP option parameters which are stored in labeled common as a result of being specified via card input:

1. The starting date of the file.

2. The number of data records to be created.

3. The bodies represented in the file.

4. The degree of the coordinate transformation curve-fits.

5. The degree of the curve-fit of the ephemeris of the fast moving body.

6. The degree of the curve-fit of the ephemeris of the slow moving bodies.

7. The number of days represented by the curve-fits.

8. The coordinate system reference, i.e., 1950.0 or true-of-date.

The fast moving body is the non-central body whose rate of change in position around the central body is greater than the other non-central bodies, i.e., slow moving bodies, requiring a greater degree for the polynomial coefficients for the position coordinates.

In generation operations 1 and 2, a direct application of the curve-fitting technique in generating a SLP ephemeris file is made. The operations begin with the writing of the SLP ephemeris tape or disk file header record reflecting the values of the SLP option parameters that are stored in labeled common.

Curve-Fitting with Chebyshev Polynomials

An initial call to the SLP ephemeris generation control subroutine SLPEPH is made to initialize quantities necessary in the curve-fitting process and to compute the time arrays for a later call to SLPEPH. Subsequently, calls are made to subroutine CHEBY which houses or treats the following basic formulation of the Chebyshev polynomial curve-fitting technique:

Chebyshev polynomials of degree m are defined by

$$T_m(x) = \cos(m \arc\cos x), \tag{2}$$

for

$$x \text{ in } [-1, 1].$$

The first and second Chebyshev polynomials are

$$T_0(x) = 1 \text{ and } T_1(x) = x. \tag{3}$$

Other Chebyshev polynomials are readily obtained by using the recurrence relation

$$T_{m+1}(x) = 2x\, T_m(x) - T_{m-1}(x) \tag{4}$$

Using equations (3) and (4) a Chebyshev series of degree m could be constructed in the form:

$$Y_m(x) = c_0 T_0(x) + c_1 T_1(x) + \ldots + c_m T_m(x) \tag{5}$$

Suppose that n points $(t_1, y_1), \ldots, (t_n, y_n)$ lying in some interval $[a, b]$ are given and we wish to find a curve approximating these points which is of the form of equation (5). The points must first be changed to the set of points x_i, $(i = 1, 2, \ldots, n)$, for which the Chebyshev polynomials are defined by using the transformation

$$x_i = \frac{2t_i - (a + b)}{b - a} \tag{6}$$

Applying the least squares criterion at this point maintains that the expression

$$S = \sum_{i=1}^{n} \left[y_i - \sum_{j=0}^{m} c_j T_j (x_i) \right]^2 \tag{7}$$

should be a minimum. To find the minimum, partial derivatives are taken with respect to the c_j, obtaining the system of simultaneous equations

$$\frac{\partial S}{\partial c_j} = 0, \quad j = 0, 1, \ldots, m \tag{8}$$

which can be written in the following matrix notation:

$$[T]\,[C] = [P],$$

where

$$[T] = \begin{bmatrix} \Sigma\, T_0^2 (x_i) & \Sigma\, T_0 (x_i)\, T_1 (x_i) & \ldots & \Sigma\, T_0 (x_i)\, T_m (x_i) \\ \Sigma\, T_1 (x_i)\, T_0 (x_i) & \Sigma\, T_1^2 (x_i) & \ldots & \Sigma\, T_1 (x_i)\, T_m (x_i) \\ \vdots & & & \vdots \\ \Sigma\, T_m (x_i)\, T_0 (x_i) & \Sigma\, T_m (x_i)\, T_1 (x_i) & \ldots & \Sigma\, T_m^2 (x_i) \end{bmatrix},$$

where Σ signifies $\sum_{i=1}^{n}$,

$$[C] = \begin{bmatrix} c_0 \\ c_1 \\ \cdot \\ \cdot \\ \cdot \\ c_m \end{bmatrix} \text{ and } [P] = \begin{bmatrix} \Sigma\, y_i\, T_0\,(x_i) \\ \Sigma\, y_i\, T_1\,(x_i) \\ \cdot \\ \cdot \\ \cdot \\ \Sigma\, y_i\, T_m\,(x_i) \end{bmatrix}.$$

The need to solve simultaneous equations can be eliminated by taking advantage of the following property of the orthogonal Chebyshev polynomials:

If k and ℓ are non-negative integers and are not both zero then,

$$\sum_{i=1}^{m+1} T_k\,(\bar{x}_i)\, T_\ell\,(\bar{x}_i) = \begin{cases} 0, & \text{for } k \neq \ell \quad (10) \\ (m+1)/2, & \text{for } k = \ell \neq 0 \quad (11) \\ m+1, & \text{for } k = \ell = 0 \quad (12) \end{cases}$$

where

$$\bar{x}_i = \cos \frac{(2i-1)\,\pi}{2\,(m+1)},\ i = 1, 2, \ldots, m+1 \tag{13}$$

The use of these nodal points yield the classical Chebyshev polynomials, and we have as opposed to relation (7),

$$\bar{S} = \sum_{i=1}^{m+1} \left[\bar{y}_i - \sum_{j=0}^{m} c_j\, T_j\,(\bar{x}_i) \right]^2 \tag{14}$$

Taking partial derivatives with respect to the c_j in this instance results in the diagonalization of [T]. Thus we have

$$[D]\,[C] = [R] \text{ or} \tag{15}$$

$$\begin{bmatrix} \Sigma T_0^2(\bar{x}_i) & 0 & \dots & 0 \\ 0 & \Sigma T_1^2(\bar{x}_i) & \dots & 0 \\ \cdot & & & \\ \cdot & & & \\ \cdot & & \cdot & \\ 0 & 0 & & \Sigma T_m^2(\bar{x}_i) \end{bmatrix} \begin{bmatrix} c_0 \\ c_1 \\ \cdot \\ \cdot \\ \cdot \\ c_m \end{bmatrix} = \begin{bmatrix} \Sigma \bar{y}_i T_0(\bar{x}_i) \\ \Sigma \bar{y}_i T_1(\bar{x}_i) \\ \cdot \\ \cdot \\ \cdot \\ \Sigma \bar{y}_i T_m(\bar{x}_i) \end{bmatrix},$$

where here, Σ signifies $\sum_{i=1}^{m+1}$.

Thus, we can now readily compute a value for each coefficient c_j,

$$c_j = \frac{\sum_{i=1}^{m+1} \bar{y}_i T_j(\bar{x}_i)}{\sum_{i=1}^{m+1} T_j^2(\bar{x}_i)}, \quad j = 0, 1, \dots, m \tag{16}$$

Using relations (11) and (12), we obtain

$$c_j = \frac{2}{m+1} \sum_{i=1}^{m+1} \bar{y}_i T_j(\bar{x}_i), \quad j \neq 0, \tag{17}$$

and

$$c_j = \frac{1}{m+1} \sum_{i=1}^{m+1} \bar{y}_i T_j(\bar{x}_i), \quad j = 0. \tag{18}$$

Having determined the coefficients c_j, the Chebyshev expansion of degree m for $\overline{Y}_m(\overline{x})$ has been completely determined:

$$\overline{Y}_m(\overline{x}) = \sum_{j=0}^{m} c_j T_j(\overline{x}). \tag{19}$$

At this point, $\overline{Y}_m(\overline{x})$ has been expressed as a Chebyshev series in the interval (-1, 1). The Chebyshev series may be converted to its equivalent power series in (-1, 1), and this series in turn may be scaled to the interval (a, b) by using the transformation

$$t = \frac{(b-a)\overline{x}}{2} + \frac{b+a}{2}. \tag{20}$$

The resulting power series may be written in the form

$$Y_m(t) = \sum_{i=1}^{m+1} A_i t^{i-1}, \tag{21}$$

where the A_i's are directly obtained from the c_j's as follows:

$$\begin{aligned} A_i = \sum_i a_{ik}, \quad & i = 1, 2, \ldots, m+1 \\ & k = j+1 = 1, 2, \ldots \\ & i + 2(k-1) \leqslant m+1 \end{aligned} \tag{22}$$

where

$$\begin{aligned} a_{1k} = (-1)^{k+1} c_{2k-1}, \quad & k = j+1, 2, \ldots \\ & 2k-1 \leqslant m+1 \end{aligned} \tag{23}$$

$$a_{i1} = 2^{i-2} c_i, \quad i = 2, 3, \ldots, m+1 \tag{24}$$

and

$$a_{ik} = c_{i+2(k-1)} \left[2a_{i-1,k} - a_{i,k-1}\right],$$
$$i = 2, 3, \ldots$$
$$k = j + 1 = 2, 3, \ldots \tag{25}$$
$$i + 2(k-1) \leqslant m + 1.$$

<u>Application in Creating a SLP File</u>

Given:

- m — degree of polynomial to be fit
- $\bar{y}$ — array of JPL ephemeris data points (m + 1 components of nutation, position, or velocity)
- $\bar{x}$ — array of times in the interval (-1, 1) that are used to get the data points

[These times are a function of m and are computed using equation (13).]

$$\bar{x}_i = \frac{\cos(2i-1)\pi}{2(m+1)}, \quad i = 1, 2, \ldots, m+1 \tag{13}$$

The coefficients (c_0, c_1, ..., c_m) are computed first using equations (17) and (18).

$$c_j = \frac{1}{m+1} \sum_{i=1}^{m+1} \bar{y}_i T_0(\bar{x}_i), \quad j \neq 0; \tag{17}$$

and

$$c_j = \frac{2}{m+1} \sum_{i=1}^{m+1} \bar{y}_i T_j(\bar{x}_i), \quad j = 0. \tag{18}$$

The expanded Chebyshev series

$$\sum_{j=0}^{m} c_j T_j(\bar{x})$$

is then converted to its equivalent power series, which in turn is scaled from the interval (-1, 1) to the interval (a, b) taking the form

$$Y_m(t) = \sum_{i=1}^{m+1} A_i (t_{i-1} - t_c)^{i-1} \qquad (26)$$

where

t_c is the time at the center of the fit
t_{i-1} is within the limits of the fit
$|b - a|$ = length of fit and a and b are the minimum and maximum values that $(t_{i-1} - t_c)$ can assume
A_i's are the various polynomial coefficients resulting from the calls to CHEBY

Since $|t - t_c| \leq 1/2$ length of the fit,

$$\underbrace{-1/2 \text{ length of fit}}_{a} \leq t - t_c \leq \underbrace{1/2 \text{ length of fit}}_{b}$$

These limits are constant during the entire time span.

The remaining subroutines and functions that are used in the generation procedure are given in Appendix B, and the overall flow of the procedure is provided by Appendix C.

B

SECTION 3

PROCEDURE FOR USING THE SLP FILE

3.1 INTRODUCTION

The SLP file contains the polynomial coefficients for the position and velocity coordinates of the fast moving body and the position coordinates for one to seven slow moving bodies. The header record of the file contains:

1. Day of the first record on the ephemeris file.

2. The year of the ephemeris file.

3. The number of records (days) on the ephemeris file.

4. The bodies represented in the file;

    a. central body

    b. fast moving body

    c. one to seven slow moving bodies.

5. The degrees of the polynomials for

    a. rotation matrix (matrices)

    b. fast moving body position

    c. fast moving body velocity

    d. slow moving body position.

6. The number of days per curve-fit.

7. The coordinate reference indicator for the SLP ephemeris (1950.0 or true-of-date coordinate system).

8. The number of bodies to be processed for the SLP ephemeris.

The remaining records on the SLP file contain:

1. The time in seconds from the start of the year of the SLP file to the midpoint of the day of the year of the SLP file.

2. The polynomial coefficients for the position coordinates of the fast moving body.

3. The polynomial coefficients for the velocity coordinates of the fast moving body.

4. The polynomial coefficients for the position coordinates of the slow moving body.

5. The polynomial coefficients for the selenocentric to selenographic transformation matrix.

6. The polynomial coefficients for the 1950.0 to true-of-date transformation matrix.

7. The polynomial coefficients for DELTA H (calculation b. of Section 2.1).

8. The day of the record.

The SLP ephemeris file is created by the program CREATE3.

The program will read the JPL DE-19 direct access ephemeris tape, compute the polynomial coefficients and write them onto the SLP ephemeris file.

3.2 JCL REQUIREMENTS

1. // EXEC PGM=CREATE3, REGION=250K

   This step will retrieve the program to generate the SLP file.

2. //STEPLIB DD DSN = TESTLOD, UNIT=2321,

   // VOL = SER = RTAC, DISP = SHR

   This step locates the program within the system.

3. //FT05F001 DD *

   File 5 will contain the input data cards describing the generation of the SLP file.

4. //FT06F001 DD SYSOUT = A

   File 6 is used by the system for printer output.

5. //FT14F001 DD DSN = XXX, UNIT = DISK,

   // DISP=(NEW,PASS), SPACE = (CYL, (4, 1))

   File 14 is used only when a SLP file is to be created on disk.

6. //FT33F001 DD UNIT = 9TRACK,

   // DCB = (RECFM=VS, BLKSIZE = 3460),LABEL=(1,BLP)

   File 33 is used only when a SLP file is to be created on tape.

7. //FT34F001 DD UNIT = 2400-9,

   // LABEL = (, BLP,, IN), VOL = SER = ABC,

   // DISP = OLD, DCB = (RECFM=VS,LRECL = 8304,

   // BLKSIZE = 8308, DEN = 2)

   File 34 describes the input DE-19 JPL ephemeris tape.

8. //FT60F001 DD DSN = GTDS .ODS. ACCOUNT,

   // DISP = SHR, UNIT = 2314, VOL=SER=G1USR1

   File 60 contains the accounting information for the GTDS system.

3.3 INPUT REQUIREMENTS

To generate the SLP file a DE-19 JPL ephemeris tape and input data cards are necessary. The JPL tape is described by file 34 and the input data cards by file 5. The data is input through NAMELIST.

The format of the input cards is:

```
SLPEPHEM
 &SLPDAT
```

Option cards as described on the next page

```
 &END
FIN
```

DATA FOR SLP EPHEMERIS FILES

CARD TYPE		FORMAT
I. DATA &SLPDAT		NAMELIST

IOPER	Operation to be performed = 3 create SLP disk file from SLP tape = 4 create SLP tape from JPL tape = 6 create SLP disk from JPL tape
SLPYMD	UTC Calendar date of start of file (YYMMDD.)
ISPAN	Number of data records to be created (Default = 1, maximum of 11 on disk file)
NBEPM(I), I=1, 9	Body numbers of bodies represented in the file (default = Earth, Moon, Sun, NDEGRE(1)=1 NBEPM (2) = 2, NBEPM (3)=3)
I=1	central body
=2	fast body
=3, 9	slow bodies

The valid NBEPM settings are:

=1 for Earth	=6 for Saturn	=11 for Venus
=2 for Moon	=7 for Uranus	
=3 for Sun	=8 for Neptune	
=4 for Mars	=9 for Pluto	
=5 for Jupiter	=10 for Mercury	

NDEGRE(I), I=1, 4 degrees of curve-fits (Defaults;

NDEGRE (1)=4, NDEGRE(2)=8, NDEGRE(3)=4), NDEGRE(4)=8

I=1	degree of coordinate transformation matrices fit (also used for GHA correction term for A.1 to UT1)
I=2	degree of position fit for NBEPM(2) (fast body)

I=3	degree of velocity fit for NBEPM(2) (fast body)
I=4	degree of position fit for NBEPM(3), ..., NBEPM(9) (slow bodies)
NCFDAY	Number of days represented by each curve-fit (Default=1)
ISLP50	Reference of SLP coordinate system (Default=1)

=1 for 1950.0
=2 for true-of-date

&END

Note: The JCL requirements for the SLP data sets are:

IOPER	FORTRAN data sets used
3	FT14F001, FT33F001
4	FT33F001, FT34F001
6	FT14F001, FT34F001

where:

FT14F001	Defines the SLP ephemeris disk file
FT33F001	Defines the SLP ephemeris tape file
FT34F001	Defines the JPL ephemeris tape file

An example of the use of CREATE3 in generating a SLP ephemeris disk file is given on the next page.

```
//CMIBTSL3 JOB (GN0141311H,T,G0J425,001003),CCC
// EXEC PGM=CREATE3,REGION=250K
//STEPLIB DD DSN=TESTLOD,UNIT=2321,VOL=SER=RTAC,DISP=SHR
//FT05F001 DD *
//FT06F001 DD SYSOUT=A
//FT13F001 DD DSN=GTDS.CDS.ERRORMSG,UNIT=2314,DISP=SHR,VOL=SER=G1USR1
//FT14F001 DD DSN=&NEWSLP,UNIT=DISK,DISP=(NEW,PASS),SPACE=(TRK,(10,1))
//FT34F001 DD UNIT=2400-9,LABEL=(,BLP,,IN),VOL=SER=30912D,DISP=OLD,
// DCB=(RECFM=VS,LRECL=8304,BLKSIZE=8308,DEN=2)
//FT60F001 DD DSN=GTDS.ODS.ACCOUNT,DISP=SHR,UNIT=2314,VOL=SER=G1USR1
//NUCLEUS DD DISP=SHR,UNIT=SYSDA,VOL=REF=SYS1.SVCLIB
IEF236I ALLOC. FOR CMIBTSL3
IEF237I 2E3/0 ALLOCATED TO STEPLIB
IEF237I 231   ALLOCATED TO FT05F001
IEF237I 334   ALLOCATED TO FT06F001
IEF237I 142   ALLOCATED TO FT13F001
IEF237I 334   ALLOCATED TO FT14F001
IEF237I 0C2   ALLOCATED TO FT34F001
IEF237I 142   ALLOCATED TO FT60F001
IEF237I 1C0   ALLOCATED TO NUCLEUS
```

PAGE 1

```
GTDS RUN NUMBER IS  1873

STARTING ADDRESS OF MAIN IS 2376992

COMPUTER IDENTIFICATION IS G1

JOB IDENTIFICATION IS CMIBTSL3

CURRENT TIME IS P3C0  3, 1972      4 I- A, 24 GUAY,   47.95000 A3 D
```

PAGE 2

```
&SLPDAT
ISPAN=        11,NBEPM=       1,        2,        3,        0,        0,        0,        0,        0,        0,
NDEGRE=       8,       8,       8,       8,NCPDAY=         1,ISLPSC=         1,IOPER=         6,SLPYMD=
  670523.000000000     ,NBSLF=         3,IDAY1 =       143,DJ=  2439633.500437654    ,IYEAR=     1967
&END
```

SECTION 4

THE USE OF THE SLP FILE

BY THE STAND-ALONE SUBROUTINE SUNRD

Once the SLP ephemeris file is created, the stand-alone subroutine SUNRD will read the polynomial coefficients for the position coordinates of the bodies in the SLP file and compute the position vectors for the bodies requested through the calling sequence of SUNRD.

Input Requirements

SUNRD requires an SLP file containing the bodies for which position vectors are requested, the Julian date, the number of the bodies requested, and the real function DJUL to execute.

SLP Ephemeris File

The SLP file to be read by SUNRD is described by file 14 as follows:

```
//GO.FT14F001 DD DSN = XXXX, UNIT = DISK,
// DISP=SHR,VOL=SER=XXXX
```

If the SLP file was temporarily created for the particular run, the DISP parameter is changed to DISP = (NEW, DELETE).

When SUNRD reads the SLP ephemeris file, it stores the parameters from the file into labelled COMMON, from SUNRD stores the header recorder into COMMON/SLPOPT/ and the remaining records in COMMON/SLPREC/. The only variables used by SUNRD from the SLP file are:

a. IDAY1 = The day of the first record on the ephemeris file

b. IYEAR = The year of the start of the ephemeris file

c. NBEPM = The central body, fast and slow moving bodies for the polynomial coefficients

d. NDEGRE(2) = The degree of the fast moving body's position

e. NDEGRE(4) = The degree of the slow moving bodies' position

f. NCFDAY = The number of days per curve-fit

g. NBSLP = The number of bodies processed for the SLP file.

h. TSEC = The time in seconds from the start of the year requested to the midpoint of the day

i. PPOLY1 = The polynomial coefficients for the position coordinates of the fast moving body

j. PPOLY2 = The polynomial coefficients for the position coordinates of the slow moving bodies

k. IDAY = The day of this particular record.

THE CALLING SEQUENCE

```
CALL SUNRD (DATE,NB,POSVEC,IERR)
```

INPUT

FORTRAN NAME	DIMENSION	DESCRIPTION
DATE	1	Julian date for which the position vectors are to be computed
NB	9	The number of the bodies requested. NB(1) = central body NB(2) = fast moving body NB(3)-NB(9) = slow moving bodies The bodies are represented by the following numbers: 1 = earth, 7 = uranus 2 = moon, 8 = neptune 3 = sun, 9 = pluto 4 = mars, 10 = mercury 5 = jupiter, 11 = venus 6 = saturn

OUTPUT

FORTRAN NAME	DIMENSION	DESCRIPTION
POSVEC	3, 8	Position vectors for the bodies requested
IERR	1	Error indicator 0 = no error 1 = I/O error 2 = error in specifying the central or fast body 3 = non-central body not in the SLP file

When an error is encountered a message will be written and the corresponding error number will be transmitted through the IERR parameter. If no error is encountered, the number 0 is transmitted.

DJUL

The real function DJUL is used to compute the modified* Julian date of a given Gregorian date after 1950.0.

The following seven pages consist of a listing and flowchart of SUNRD and a listing of DJUL.

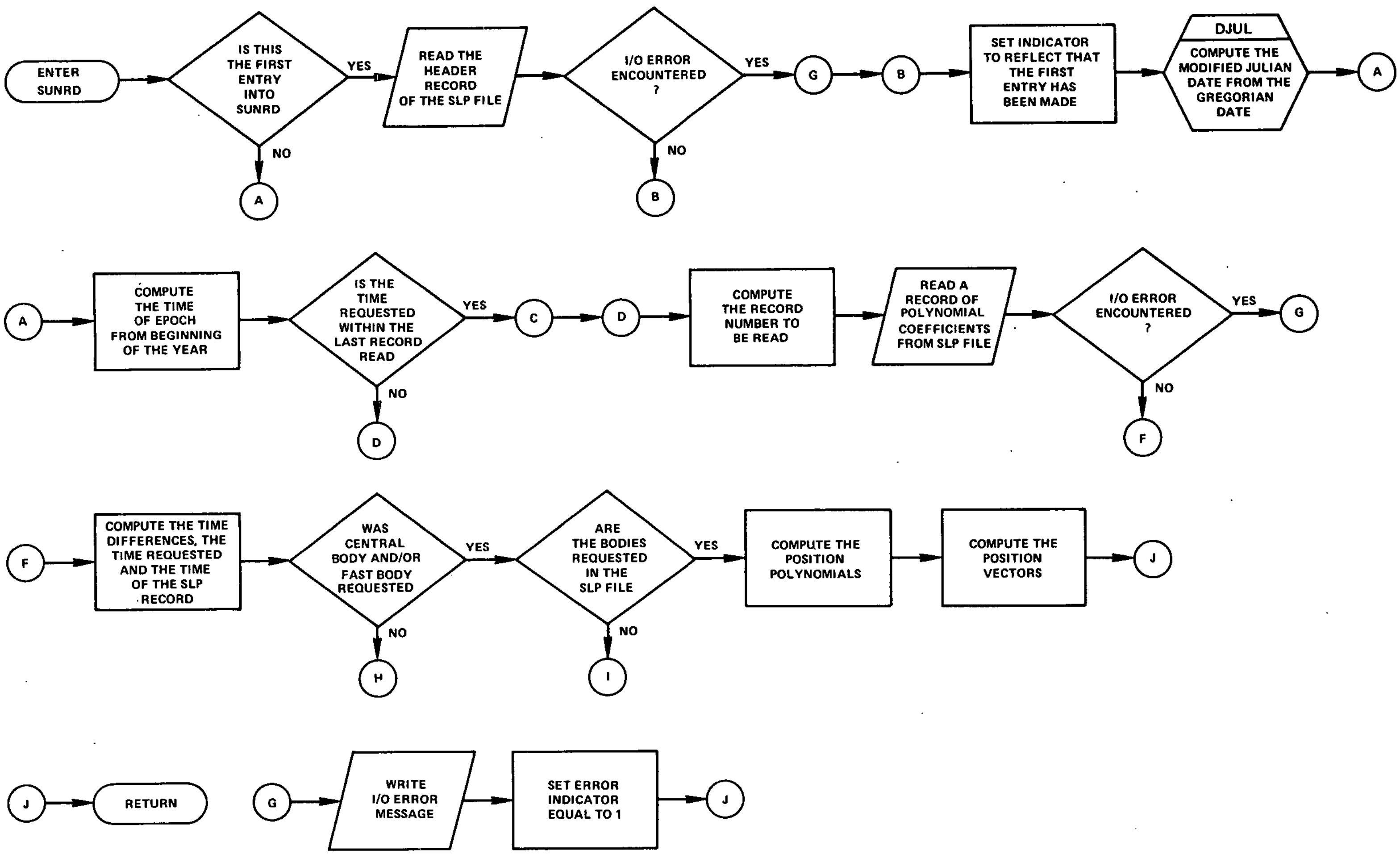
*Modified Julian Date = Julian Date - 2430000.

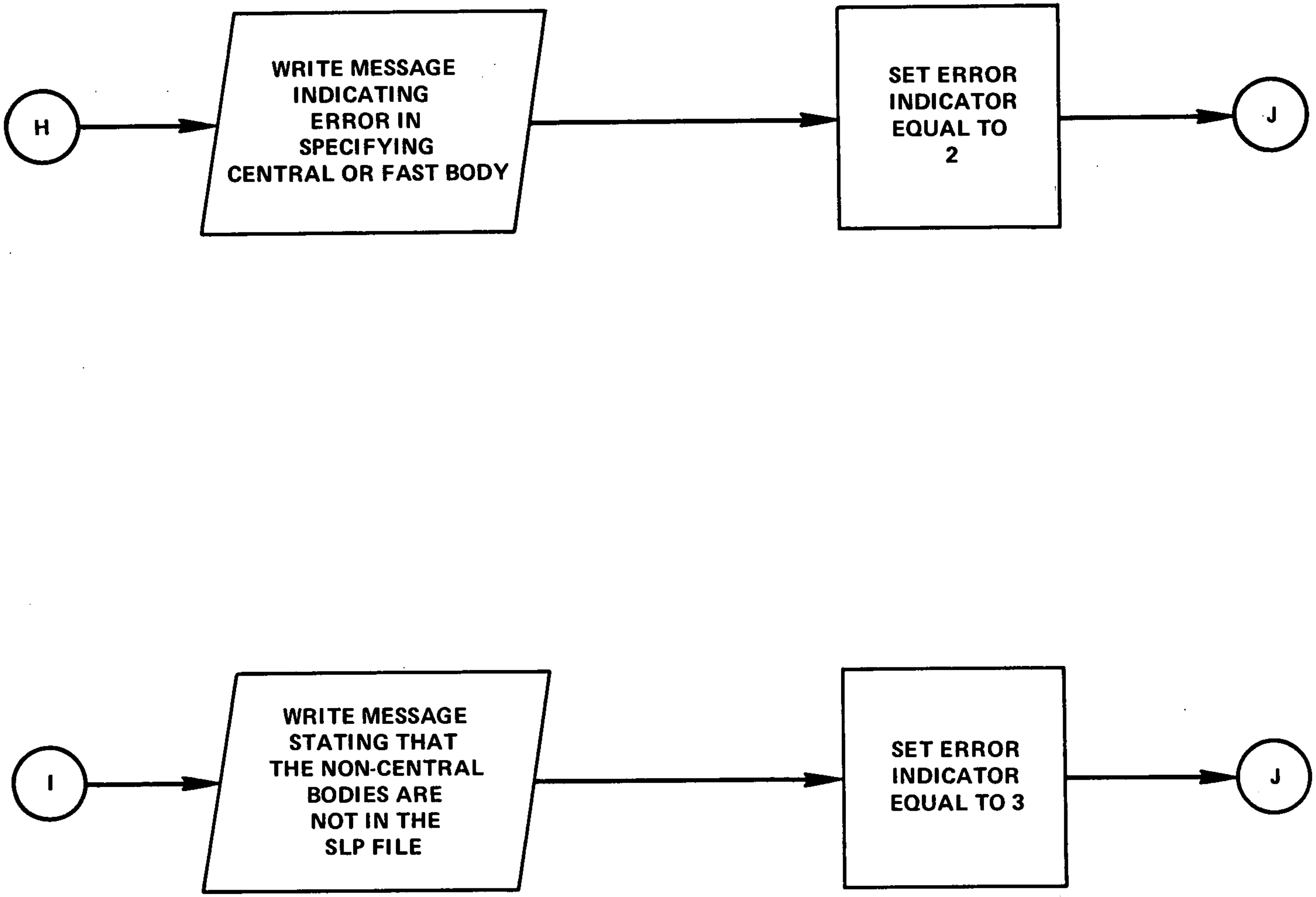
```
         COMPILER OPTIONS - NAME=  MAIN,OPT=01,LINECNT=58,SIZE=0000K,
                            SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,XREF
ISN 0002               SUBROUTINE SUNRD (DATE,NB,POSVEC,IERR)
                 C*********************************************************************
                 C
                 C
                 C      VERSION OF 08/01/72
                 C      VERSION OF 11/9/71
                 C      VERSION OF 12/1/72
                 C          FORTRAN H SUBROUTINE FOR IBM S/360
                 C      PURPOSE
                 C          TO COMPUTE THE POSITION VECTORS
                 C      CALLING SEQUENCE
                 C          CALL SUNRD(DATE,NB,POSVEC,IERR)
                 C      INPUT
                 C          CALLING SEQUENCE
                 C                DATE  -  JULIAN UNIVERSAL DATE
                 C                NB    -  THE BODIES REQUESTED
                 C                         NB(1) - CENTRAL BODY
                 C                         NB(2) - THE FAST MOVING BODY
                 C                         NB(3+K) - THE SLOW MOVING BODIES
                 C      OUTPUT
                 C          CALLING SEQUENCE
                 C          POSVEC - THE POSITION VECTORS FOR THE BODIES SPECIFIED
                 C                      IN THE NB ARRAY
                 C
                 C                IERR  -  ERROR INDICATOR
                 C                           0 - NO ERROR
                 C                           2 - ERROR IN SPECIFYING THE CENTRAL OF FAST
                 C                               BODY
                 C                           3 - NON-CENTRAL BODY NOT IN THE SLP-FILE
                 C
                 C     COMMON BLOCK INFORMATION USED INTERNALLY
                 C          COMMON /SLPCFT/
                 C                IDAY1   - DAY OF FIRST RECORD ON EPHEMERIS FILE
                 C                IYEAR   -  YEAR OF THE EPHEMERIS FILE
                 C                NBEPM   - BODIES FOR POLYNOMIAL COEFFICIENTS
                 C                           NBEPM(1)    - CENTRAL BODY
                 C                           NBEPM(2)  - FAST MOVING BODY
                 C                           NBEPM(3+K) - SLOW MOVING BODIES
                 C                NDEGRE - DEGREE OF POLYNOMIALS
                 C                           NDEGRE(2) - FAST MOVING BODY POSITION DEGREE
                 C                           NDEGRE(4) - SLOW MOVING BODIES POSITION DEGREE
                 C                NCFDAY - NUMBER OF DAYS PER CURVE FIT
                 C                NBSLP  - NUMBER OF BODIES ON FILE
                 C          COMMON /SLPREC/
                 C                TSEC   - TIME IN SECONDS FROM START OF THIS YEAR
                 C                         TO MIDPOINT OF THIS RECORD TIME INTERVAL
                 C                PPOLY1 - THE POLYNOMIAL COEFFICIENTS FOR THE FAST
                 C                         MOVING BODY
                 C                PPOLY2 - POLYNOMIAL COEFFICIENTS FOR THE SLOW
                 C                         MOVING BODIES
                 C                IDAY   - BEGINNING DAY OF THIS RECORD
                 C
                 C*********************************************************************
                 C
```

```
ISN 0003          IMPLICIT REAL*8 (A-H,O-Z)
ISN 0004          LOGICAL FIRST
ISN 0005          COMMON/SLPOPT/ DJ          ,IDAY1    ,IYEAR    ,ISPAN      ,NBEPM(9) ,
                 *                NDEGRE(4) ,NCFDAY   ,ISLP50   ,NHSLP
ISN 0006          COMMON/SLPREC/ TSEC        ,PPOLY1(3,20)        ,VPOLY1(3,13)     ,
                 1                PPOLY2(3,13,7)       ,APOLY(3,3,10)       ,
                 2                CPOLY(3,3,10)        ,PDELH(10),IDAY
ISN 0007          DIMENSION      EPTIME(20),BB(3,8)   ,POSVEC(3,8)         ,NB(9)     ,
                 1                ISUB(9)
ISN 0008          DATA           IDPREV/-99999999/    ,FIRST/.TRUE./       ,NWSLP/14/
ISN 0009          DATA TOL /1.0D-30/
ISN 0010          DEFINE FILE 14(100,1127,U,IAV)
ISN 0011          IERR = 0
            C
            C     IS THIS THE FIRST ENTRY-INTO SUNRD --- NO
            C
ISN 0012          IF (.NOT. FIRST) GO TO 2
            C
            C        READ EPHEMERIS HEADER READ AND STORE IN COMMON/SLPOPT/
            C
ISN 0014          READ(NWSLP'1,ERR=800)           IDAY1, IYEAR, ISPAN, NBEPM,
                 *NDEGRE, NCFDAY, ISLP50 , NHSLP
            C
ISN 0015          FIRST = .FALSE.
            C
ISN 0016          Y = DFLOAT (IYEAR - (IYEAR/100) * 100 )
            C
            C        CONSTANT A1 -UTC  OFFSET FOR 1967
            C
ISN 0017          A1UTC = 5.662528D0
            C
ISN 0018          DJULE=DJUL(Y,1.D0,1.D0,0.D0,0.D0,0.D0)+2433000.0D0
            C
            C        IS DAY IN SAME INTERVAL AS PREVIOUS DAY
            C
ISN 0019        2 T=(DATE -DJULE)*86400.0D0 + A1UTC
ISN 0020          IDAYR = IDINT(T / 86400.0D0) + 1
ISN 0021          IF (IDAYR .GE. IDPREV .AND. IDAYR .LT. (IDPREV+NCFDAY)) GO TO 3
ISN 0023          IREC = ((IDAYR - IDAY1) / NCFDAY) + 2
            C
            C        READ EPHEMERIS COEFFICIENTS
            C
ISN 0024          READ(NWSLP'IREC,ERR=800) TSEC,PPOLY1,VPOLY1,PPOLY2,APOLY,CPOLY,
                 1                          PDELH,IDAY
            C
ISN 0025          IDPREV = IDAY
ISN 0026        3 EPTIME(1) = ((T - TSEC) / 86400.0D0)
ISN 0027          MAX = MAX0 (NDEGRE(2),NDEGRE(4))
ISN 0028          DO 4 I = 2,MAX
ISN 0029          EPTIME(I) = EPTIME(1) * EPTIME(I-1)
ISN 0030          IF(DABS(EPTIME(I)).LT.TOL) EPTIME(I)=0.0D0
ISN 0032        4 CONTINUE
ISN 0033          IF(NB(1).EQ.0.OR.NB(2).EQ.0) GO TO 930
ISN 0035          NBCENT=99999999
ISN 0036          NAR = 0
ISN 0037          I = 0
```

```
ISN 0038           K = 0
ISN 0039       100 I = I + 1
ISN 0040           IF(I.EQ.10) GO TO 200
ISN 0042           IF(NB(I).EQ.0) GO TO 200
ISN 0044           NAR = NAR + 1
ISN 0045           DO 150 J=1,NBSLP
ISN 0046           IF(NB(I).EQ.NBEFN(J)) GO TO 175
ISN 0048       150 CONTINUE
ISN 0049           GO TO 930
ISN 0050       175 IF(J.EQ.1) GO TO 180
ISN 0052           K = K + 1
ISN 0053           ISUB(K) = J - 1
ISN 0054           GO TO 100
ISN 0055       180 NBCENT = I-1
ISN 0056           GO TO 100
ISN 0057       200 CONTINUE
ISN 0058           NFBDG = NDEGRE(2) + 1
ISN 0059           NSBDG = NDEGRE(4) + 1
             C                                                       00000236
             C        EVALUATE POSITION POLYNOMIALS                  00000237
             C                                                       00000238
ISN 0060       215 DO 220 JJ=1,K
ISN 0061           J = ISUB(JJ)
ISN 0062           IF(J.EQ.1) GO TO 230
ISN 0064           JM1 = J -1
ISN 0065           BB(1,JJ) = PPOLY2(1,1,JM1)
ISN 0066           BB(2,JJ) = PPOLY2(2,1,JM1)
ISN 0067           BB(3,JJ) = PPOLY2(3,1,JM1)
ISN 0068           DO 220 I=2,NSBDG
ISN 0069           BB(1,JJ) = BB(1,JJ) + PPOLY2(1,I,JM1) * SPTIME(I-1)
ISN 0070           BB(2,JJ) = BB(2,JJ) + PPOLY2(2,I,JM1) * SPTIME(I-1)
ISN 0071           BB(3,JJ) = BB(3,JJ) + PPOLY2(3,I,JM1) * SPTIME(I-1)
ISN 0072           GO TO 220
ISN 0073       230 BB(1,JJ) = PPOLY1(1,1)
ISN 0074           BB(2,JJ) = PPOLY1(2,1)
ISN 0075           BB(3,JJ) = PPOLY1(3,1)
ISN 0076           DO 240 I=2,NFBDG
ISN 0077           BB(1,JJ) = BB(1,JJ) + PPOLY1(1,I) * SPTIME(I-1)
ISN 0078           BB(2,JJ) = BB(2,JJ) + PPOLY1(2,I) * SPTIME(I-1)
ISN 0079           BB(3,JJ) = BB(3,JJ) + PPOLY1(3,I) * SPTIME(I-1)
ISN 0080       240 CONTINUE
ISN 0081       220 CONTINUE
ISN 0082           K = 1
ISN 0083           NAR = NAR - 1
ISN 0084           IF(NBCENT.EQ.0) K = 0
             C                                                       00000297
             C        OUTPUT POSITION VECTORS                        00000307
             C                                                       00000308
ISN 0086           DO 260 J=1,NAR
ISN 0087           IF(J-NBCENT)270,280,290
ISN 0088       270 POSVEC(1,J) = BB(1,J+1) - BB(1,1)
ISN 0089           POSVEC(2,J) = BB(2,J+1) - BB(2,1)
ISN 0090           POSVEC(3,J) = BB(3,J+1) - BB(3,1)
ISN 0091           GO TO 260
ISN 0092       280 POSVEC(1,J) = -BB(1,1)
ISN 0093           POSVEC(2,J) = -BB(2,1)
```

```
ISN 0094            POSVEC(3,J) = -BB(3,1)
ISN 0095            GO TO 260
ISN 0096       250  POSVEC(1,J) = BB(1,J) - K*BB(1,1)
ISN 0097            POSVEC(2,J) = BB(2,J) - K*BB(2,1)
ISN 0098            POSVEC(3,J) = BB(3,J) - K*BB(3,1)
ISN 0099       260  CONTINUE
ISN 0100            GO TO 999
               C                                                          00000315
ISN 0101       900  WRITE(6,1400)
ISN 0102            IERR = 1
ISN 0103      1400  FORMAT('0I/O ERROR')
ISN 0104            GO TO 999
ISN 0105       920  WRITE(6,1000)
ISN 0106            IERR = 2
ISN 0107      1000  FORMAT('0 ERROR IN SPECIFYING THE CENTRAL AND/OR FAST BODY')
ISN 0108            GO TO 999
ISN 0109       930  WRITE(6,1001)
ISN 0110            IERR = 3
ISN 0111      1001  FORMAT('0 NON-CENTRAL BODIES NOT IN FILE.')
ISN 0112       999  RETURN
               C    ************************                              00000316
ISN 0113            END
```


ENTER SUNRD
IS THIS THE FIRST ENTRY INTO SUNRD
YES
NO
A
READ THE HEADER RECORD OF THE SLP FILE
I/O ERROR ENCOUNTERED ?
YES
NO
B
G
B
SET INDICATOR TO REFLECT THAT THE FIRST ENTRY HAS BEEN MADE
DJUL
COMPUTE THE MODIFIED JULIAN DATE FROM THE GREGORIAN DATE
A
A
COMPUTE THE TIME OF EPOCH FROM BEGINNING OF THE YEAR
IS THE TIME REQUESTED WITHIN THE LAST RECORD READ
YES
NO
D
C
D
COMPUTE THE RECORD NUMBER TO BE READ
READ A RECORD OF POLYNOMIAL COEFFICIENTS FROM SLP FILE
I/O ERROR ENCOUNTERED ?
YES
G
NO
F
F
COMPUTE THE TIME DIFFERENCES, THE TIME REQUESTED AND THE TIME OF THE SLP RECORD
WAS CENTRAL BODY AND/OR FAST BODY REQUESTED
YES
NO
H
ARE THE BODIES REQUESTED IN THE SLP FILE
YES
NO
I
COMPUTE THE POSITION POLYNOMIALS
COMPUTE THE POSITION VECTORS
J
J
RETURN
G
WRITE I/O ERROR MESSAGE
SET ERROR INDICATOR EQUAL TO 1
J


H
WRITE MESSAGE INDICATING ERROR IN SPECIFYING CENTRAL OR FAST BODY
SET ERROR INDICATOR EQUAL TO 2
J
I
WRITE MESSAGE STATING THAT THE NON-CENTRAL BODIES ARE NOT IN THE SLP FILE
SET ERROR INDICATOR EQUAL TO 3
J

```
LEVEL 20.1 (AUG 71)                    OS/360  FORTRAN H                        DATE  72.339/17.41.30

        COMPILER OPTIONS - NAME=  MAIN,OPT=01,LINECNT=58,SIZE=0000K,
                           SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,XREF
                  C
   ISN 0002               REAL FUNCTION DJUL*8(Y,XM,D,HR,TM,SEC)
                  C
                  C   ****************************************************************
                  C
                  C       VERSION OF 2/30/71
                  C         FORTRAN FUNCTION SUBPROGRAM
                  C
                  C       PURPOSE
                  C         TO COMPUTE THE MODIFIED JULIAN DATE OF A GIVEN GREGORIAN
                  C         DATE AFTER 1950.0  (JULIAN DATE - 2430000 )
                  C
                  C       USAGE
                  C         REAL FUNCTION DJUL(Y,XM,D,HR,TM,SEC)
                  C
                  C       INPUT
                  C           X - YEAR
                  C          XM - MONTH
                  C           D - DAY
                  C          HR - HOURS
                  C          TM - MINUTES
                  C         SEC - SECONDS
                  C
                  C       OUTPUT
                  C           DJUL - THE MODIFIED JULIAN DATE
                  C
                  C       REMARKS
                  C         INPUT DATE MUST OCCURE AFTER 1950.0
                  C
                  C       SUBROUTINES REQUIRED
                  C           NONE
                  C       PROGRAMMER
                  C         M. MC GARRY
                  C
                  C   ****************************************************************
                  C
   ISN 0003               IMPLICIT REAL*8 (A-H,O-Z)
   ISN 0004               I=Y+1900.0D0
   ISN 0005               J=XM
   ISN 0006               K=D
   ISN 0007               FR=
                         1   ((HR - 12.0D0) * 3600.0D0 + TM * 60.0D0 + SEC) / 86400.0D0
   ISN 0008               DJUL=K-32075+1461*(I+4800+(J-14)/12)/4+367*(J-2-(J-14)/12*12)/12-3
                         $*((I+4900+(J-14)/12)/100)/4- 2430000
   ISN 0009               DJUL   = DJUL + FR
   ISN 0010               RETURN
   ISN 0011               END
```

The following is an example of a DRIVER for SUNRD. This DRIVER indicates the bodies and date for which the position vectors are requested. After each call the position vectors are written out by this driver.

```
LEVEL 20.1 (AUG 71)                    OS/360  FORTRAN H                              DATE  72.339/17.42.59

      COMPILER OPTIONS - NAME=  MAIN,OPT=01,LINECNT=58,SIZE=0000K,
                         SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,XREF
  ISN 0002              IMPLICIT REAL *8(A-H,O-Z)
  ISN 0003              DEFINE FILE 14(20,1127,U,II)
  ISN 0004              DIMENSION NB(9),POSVEC(3,8)
  ISN 0005              DO 9 J=1,9
  ISN 0006            9 NB(J)=0
  ISN 0007              NB(1) = 1
  ISN 0008              NB(2) = 5
  ISN 0009              NB(3) = 9
  ISN 0010              DATE = 2439633.5D0
  ISN 0011              CALL SUNRD(DATE,NB,POSVEC,IERR)
  ISN 0012              WRITE(6,1234)POSVEC
  ISN 0013              DATE = DATE + .5D0
  ISN 0014              CALL SUNRD(DATE,NB,POSVEC,IERR)
  ISN 0015              WRITE(6,1234)POSVEC
  ISN 0016              DATE = DATE + .5D0
  ISN 0017              CALL SUNRD(DATE,NB,POSVEC,IERR)
  ISN 0018              WRITE(6,1234)POSVEC
  ISN 0019              NB(1) = 1
  ISN 0020              NB(2) = 2
  ISN 0021              NB(3) = 4
  ISN 0022              NB(4) = 11
  ISN 0023              DATE = 2439633.5D0
  ISN 0024              CALL SUNRD(DATE,NB,POSVEC,IERR)
  ISN 0025              WRITE(6,1234)POSVEC
  ISN 0026              DATE = DATE + .5D0
  ISN 0027              CALL SUNRD(DATE,NB,POSVEC,IERR)
  ISN 0028              WRITE(6,1234)POSVEC
  ISN 0029              DATE = DATE + .5D0
  ISN 0030              CALL SUNRD(DATE,NB,POSVEC,IERR)
  ISN 0031              WRITE(6,1234)POSVEC
  ISN 0032              NB(1) = 4
  ISN 0033              NB(2) = 1
  ISN 0034              NB(3) = 11
  ISN 0035              NB(4) = 7
  ISN 0036              NB(5) = 2
  ISN 0037              DATE = 2439633.5D0
  ISN 0038              CALL SUNRD(DATE,NB,POSVEC,IERR)
  ISN 0039              WRITE(6,1234)POSVEC
  ISN 0040              DATE = DATE + .5D0
  ISN 0041              CALL SUNRD(DATE,NB,POSVEC,IERR)
  ISN 0042              WRITE(6,1234)POSVEC
  ISN 0043              DATE = DATE + .5D0
  ISN 0044              CALL SUNRD(DATE,NB,POSVEC,IERR)
  ISN 0045              WRITE(6,1234)POSVEC
  ISN 0046         1234 FORMAT('0',10X,'POSVEC',/,2X,8(/,3X,3(5X,D17.8)))
  ISN 0047              RETURN
  ISN 0048              END
```

SECTION 5

ACCURACY OF THE CHEBYSHEV REPRESENTATION

Specifying the earth as the central body, the moon as the fast moving body, and the sun as the slow moving body, the accuracy of the Chebyshev representation of the lunar ephemeris was examined as a function of the two SLP option parameters specifying:

1. The degree of the curve-fit of the lunar ephemeris (values of 6 through 19 were used)

2. The number of days represented by the curve-fits (values of 1 through 28 were used)

Other SLP option parameters were set as shown in parenthesis:

- The degree of the coordinate transformation curve-fits (4)

- The degree of the curve-fit of the ephemeris of the slow moving body (4)

- The coordinate system reference (1950.0)

- The starting date of the file (720101)

The rms (673 points) errors in position for the polynomial approximations are presented in Figure 5-1 and were obtained using

$$\text{rms error} = \left[\left(\sum_{i=1}^{673} (O_i - C_i)^2 \right) / 673 \right]^{1/2}$$

where

O_i = the JPL system value (not quite as accurate as 0.2 Km)

C_i = the GTDS system value

The rms values represented by the graphs are the "scaled rms" values. They should be multiplied by $1/\sqrt{673} \approx 1/25.94$ to obtain the actual rms values. A sample test run is given by Figure 5-2.

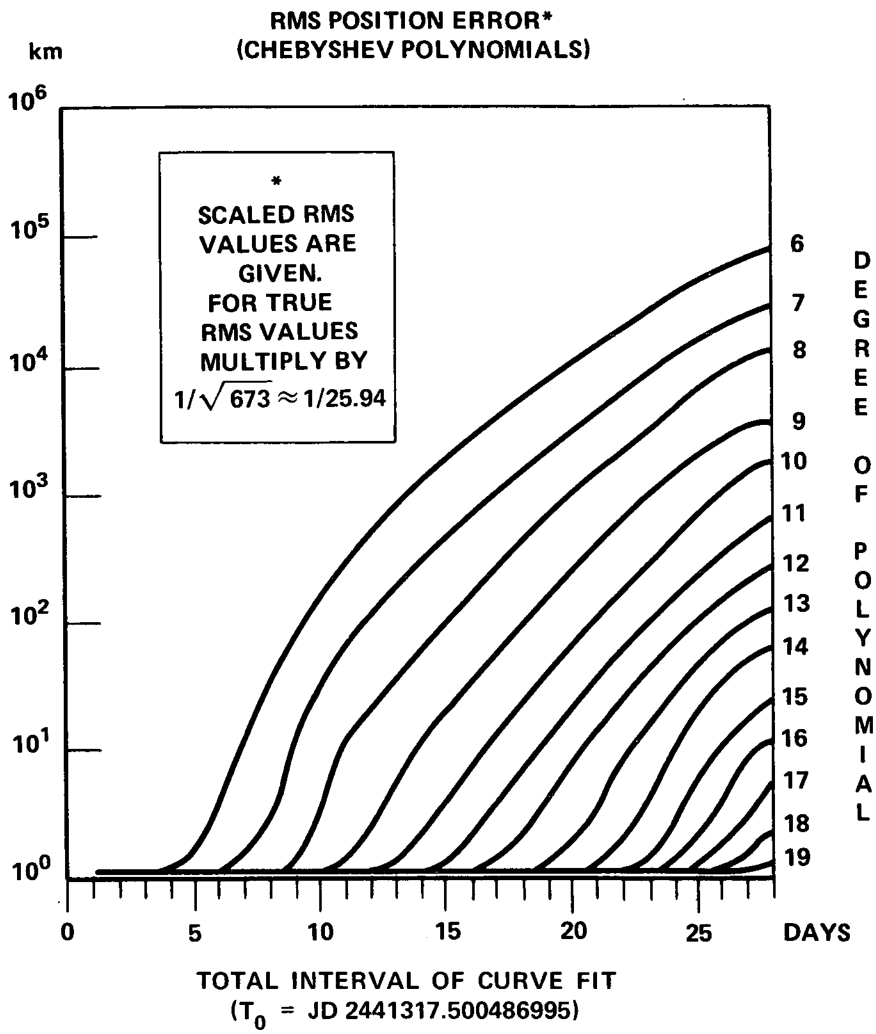


Figure 5-1. RMS Position Error of Curve Fit as a Function of Total Interval and Degree of Polynomial

Sample lunar position and velocity SLP file accuracies comparable to the JPL ephemeris are given in Table 5-1. The results show that the Chebyshev representation is indeed within the accuracy of the JPL ephemeris system for long arc lengths of approximately 28 days when the corresponding degree of the polynomial fit is chosen sufficiently high.

```
GTDS RUN NUMBER IS  2807

STARTING ADDRESS OF MAIN IS 1384688

COMPUTER IDENTIFICATION IS G1

JOB IDENTIFICATION IS GIMGACCC

CURRENT TIME IS JULY 24, 1972   20 HRS , 59 MINS,  26.89999 SECS


&SLPCAT
ISPAN=        2,NBEPM=        1,        2,        3,NDEGRE=        4,        19,        4,NCFDAY=        28,ISLP50=
      1,IOPER=        6,SLPYMD=  720101.0000000000    ,NBSLP=        3,IDAY1=        1,DJ=  2441317.500486995    ,IYEAR=
    1972
&END
IOPER = 6, CREATE SLP PERMANENT FILE FROM JPL TAPE


RMS POSITION ERROR =         0.6593025236815700D-01   ( 0.1710379701419598D 01 = SCALED RMS)

RMS VELOCITY ERROR =         0.6698238262325067D-06   ( 0.1737673283045557D-04 = SCALED RMS)

MAX. POSITION ERROR =        0.1372835890241937D 00

MAX. VELOCITY ERROR =        0.1309953323995595D-05        K =  673
HEADER RECORD
   IYEAR = 1972
     IDAY1 =     1
     ISPAN =     2
     NBEPM(1) =     1
     NBEPM(2) =     2
     NBEPM(3) =     3
     NDEGRE(1) =     4
     NDEGRE(2) =    19
     NDEGRE(3) =     4
     NCFDAY =    28
     ISLP50 =     1
     NBSLP =     3
```

Figure 5-2

Table 5-1

Sample Lunar Position[1] & Velocity[2] SLP File
Accuracies Comparable to the JPL Ephemeris*

DEGREE	ARC LENGTH**	RMS Error of Chebyshev Representation	DEGREE	ARC LENGTH	RMS Error of Chebyshev Representation
6	5	0.0721 Km[1] 0.367×10^{-6} Km/sec[2]	10	14	0.1370 Km[1] 0.140×10^{-5} Km/sec[2]
6	6	0.2063 0.120×10^{-5}	10	15	0.2068 0.231×10^{-5}
7	8	0.1785 0.119×10^{-5}	11	16	0.1245 0.121×10^{-5}
7	9	0.3867 0.259×10^{-5}	11	17	0.2126 0.218×10^{-5}
8	10	0.1699 0.134×10^{-5}	12	18	0.1237 0.117×10^{-5}
8	11	0.4076 0.322×10^{-5}	12	19	0.2031 0.200×10^{-5}
9	12	0.1740 0.156×10^{-5}	13	21	0.1898 0.181×10^{-5}
9	13	0.2908 0.279×10^{-5}	13	22	0.3340 0.327×10^{-5}

*Accuracy ≈ 0.2 Km.
**Arc Length is Expressed in Days.

Table 5-1 (Continued)

DEGREE	ARC LENGTH	RMS Error of Chebyshev Representation	DEGREE	ARC LENGTH	RMS Error of Chebyshev Representation
14	22	0.1194 Km[1] 0.112 x 10^{-5} Km/sec[2]	17	27	0.1556 Km[1] 0.180 x 10^{-5} Km/sec[2]
14	23	0.2179 0.215 x 10^{-5}	17	28	0.2542 0.295 x 10^{-5}
15	24	0.1509 0.158 x 10^{-5}	18	28	0.1191 0.139 x 10^{-5}
15	25	0.2753 0.295 x 10^{-5}			
16	25	0.1142 0.124 x 10^{-5}	19	28	0.0659 0.669 x 10^{-6}
16	26	0.2029 0.229 x 10^{-5}			

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REFERENCES

1. Computer Sciences Corporation, 5035-23700-01TM, Draft Material for the Goddard Trajectory Determination Subsystem Design Manual, J. E. Dunn, Jr., N. R. Burton, and J. Fein, April 1972.

2. TRW Systems Group, TRW 66-FMT-491, Polynomial Approximations for Short-Arc Lunar Ephemerides, J. B. Clifford, Jr., M. R. Hopkins, and G. M. Gilbert, February 1967.

3. Jet Propulsion Laboratory, 32-1181, JPL Development Ephemeris Number 19, C. J. Devine, November 1967.

4. Jet Propulsion Laboratory, 32-580, User's Description of JPL Ephemeris Tapes, Peabody, Scott, and Orozeo, March 1964.

5. Kuo, Shan S., Numerical Methods and Computers, Addison-Wesley Publishing Co., Massachusetts, July 1966.

6. Computer Sciences Corporation, 9101-03500-02TM, Use of JPL Ephemeris Data in the Goddard Trajectory Determination Subsystem (GTDS), Kotsakis, G., September 1972.

APPENDIX A

JPL EPHEMERIS SYSTEM IN BRIEF

The data contained on the JPL DE-19 tapes which collectively span the time interval from December 30, 1949 to January 1, 2000 may be represented in the following tabular form:

t	t_0			t_f
r	r_0	r_1	. . .	r_f
$\dot{r}$	$\dot{r}_0$	$\dot{r}_1$	. . .	$\dot{r}_f$
$\Delta\psi$	$\Delta\psi_0$	$\Delta\psi_1$	. . .	$\Delta\psi_f$
$\Delta\epsilon$	$\Delta\epsilon_0$	$\Delta\epsilon_1$	. . .	$\Delta\epsilon_f$
$\Delta\dot{\psi}$	$\Delta\dot{\psi}_0$	$\Delta\dot{\psi}_1$	. . .	$\Delta\dot{\psi}_f$
$\Delta\dot{\epsilon}$	$\Delta\dot{\epsilon}_0$	$\Delta\dot{\epsilon}_1$	. . .	$\Delta\dot{\epsilon}_f$
d^2Q	d^2Q_0	d^2Q_1	. . .	d^2Q_f
d^4Q	d^4Q_0	d^4Q_1	. . .	d^4Q_f

where

r = fitted integration positions of the planets of the solar system, the earth-moon barycenter, and the earth's moon.

$\dot{r}$ = corresponding fitted integration velocities

$\Delta\psi$ = moon nutations in longitude

$\Delta\epsilon$ = moon nutations in obliquity

$\Delta\dot{\psi}$ and $\Delta\dot{\epsilon}$ = corresponding nutation rates

d^2Q = second modified differences of the above quantities

d^4Q = fourth modified differences of the above quantities

t_0 = initial Julian date for which data are provided

t_f = final Julian date for which data are provided

stepsize for lunar data, $\Delta\psi$ and $\Delta\epsilon$ = 1/2 day

stepsize for mercury data = 2 days

stepsize for all other data = 4 days

Positions and velocities are referred to the rectangular equatorial reference frame of the mean equator and equinox of 1950.0 = Julian date (JD) 243 3282.423.

Planetary data are heliocentric and are expressed in astronomical units (AU) and AU/day, and lunar data are geocentric and are expressed in units called "earth radii" and "earth radii/day".

The lunar and planetary data were generated by a least-squares fit to source positions obtained on the basis of current planetary theories. Velocity coordinates for the lunar ephemeris and nutation rates were computed by numerical differentiation, while planet position and velocity coordinates were obtained as a numerical integration fit to source positions. The uncertainty in the geocentric position of the moon's center of mass is estimated at 150 meters, and the uncertainty in the distance is approximately 60 meters. Modified second and fourth differences are retained to facilitate the use of Everett's fifth-order interpolation formula in calculating intermediate values. The truncation error bounds associated with the interpolation formula are given in Table A-1. Optionally, data reduction can be achieved by curve-fitting techniques at the risk of a possible loss in accuracy.

Table A-1

Bound for Truncation Error
When Using Fifth-Order Everett Interpolation Formula*

Body	Position	Velocity
Mercury	8890.00 AU	4420.00 AU/Day
Venus	4.73 AU	0.62 AU/Day
Earth-Moon Barycenter	5.19 AU	2.50 AU/Day
Mars	6.74 AU	5.77 AU/Day
Jupiter	6.64 AU	5.72 AU/Day
Saturn	6.64 AU	5.72 AU/Day
Uranus	6.64 AU	5.72 AU/Day
Neptune	6.64 AU	5.72 AU/Day
Pluto	6.64 AU	5.72 AU/Day
Moon	10100.00 Earth Radii	14500.00 Earth Radii/Day
$\Delta\psi$	0.46 Radii	1.16 Radii/Day
$\Delta\epsilon$	0.23 Radii	0.58 Radii/Day

*All entries have been multiplied by 10^{12}

The above table is taken from Reference 3.

APPENDIX B

SUBROUTINES AND FUNCTIONS NEEDED TO CREATE A SLP FILE FROM A JPL TAPE

MAIN	— identify and initiate the permanent file maintenance operations
AMATRX	— computes transformation matrix which rotates from selenocentric to selenographic
CHEBY	— fits the Chebyshev polynomial of degree mn through the points F. This polynomial is then converted to its equivalent power series and scaled to the closed interval [XMIN, XMAX].
CMATRX	— computes transformation matrix which rotates mean equator and equinox of 1950.0 to true-of-date
DELTIM	— computes time in seconds relative to a reference date, or the Julian date, given a packed calender date
DIFF	— calculates the differences between any two time points in the 20th Century
DJUL	— computes modified Julian date of a given Gregorian date after 1950.0
ENQ	— (a) contains entry point — DEQ (b) provides data set integrity for GTDS data sets
ERROUT	— retrieves error messages from the permanent data base and sends it to the printer
GETTAP	— reads and handles DE-19 tape for READE
INPUT1	— controls retrieval of the ephemeris data from the JPL tape
MA3331	— computes the product of a 3 x 3 matrix and a 3 x 1 matrix
PAGER	— (a) contains entry point-PAGENP (b) provides paging control to printer
READE	— retrieves, interpolates, and translates ephemeris data from the JPL Ephemeris Tape

RPDAT0 — obtains current date from OS/360 system

RYMDI — separates 6-digit packed calender date into two-digit words

SETDAF — supplies data control block information to FORTRAN I/O routines

SETSLP — reads options and initializes creation of the SLP file

SLPEPH — controls the retrieval of the interpolated and translated JPL ephemeris data and computes the Chebyshev polynomial coefficients for output

SLPPF — (a) contains entry points: JPLTPF & SLPTPF

(b) creates SLP ephemeris permanent file

SLPTAP — generates SLP ephemeris tape

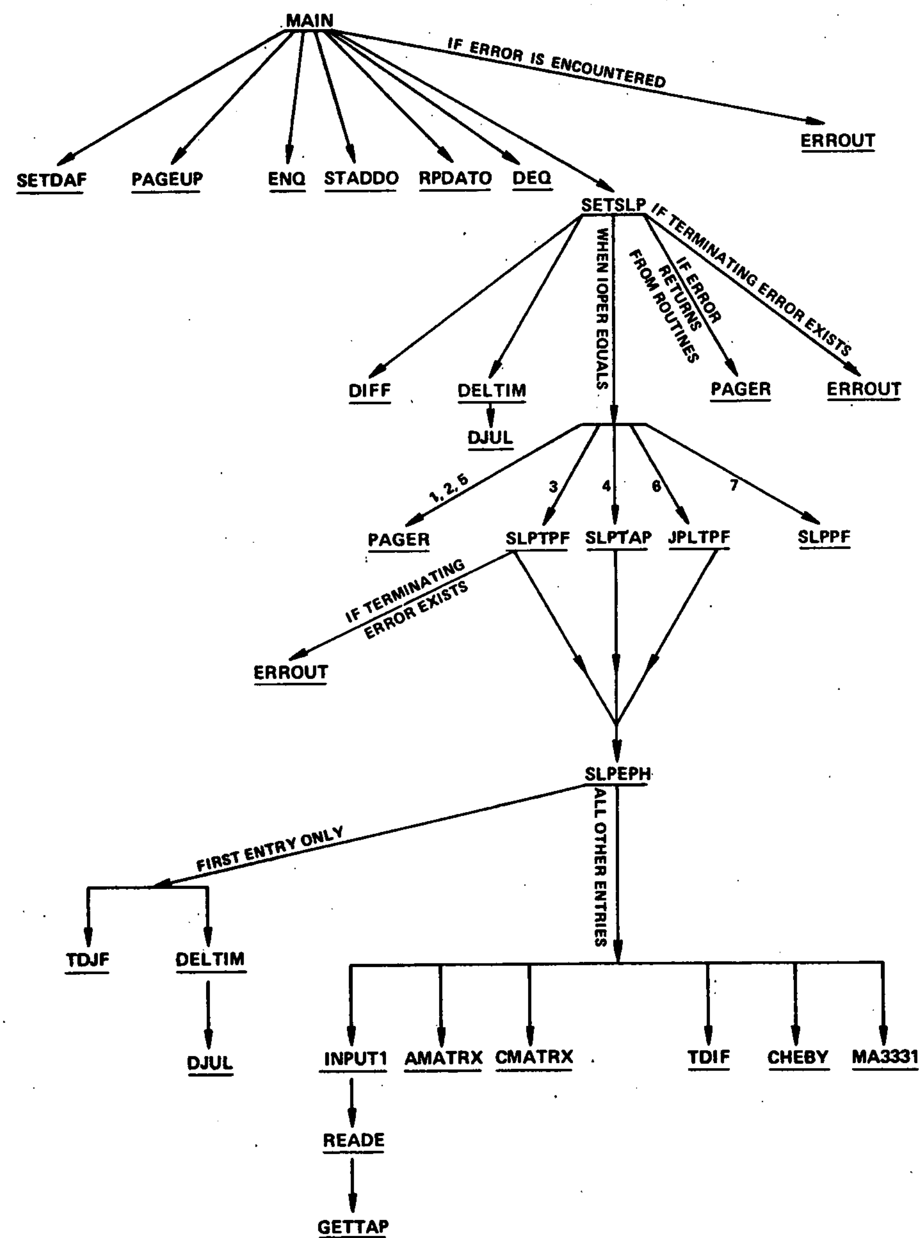
STADR0 — provides accounting information

TDIF — computes time differences

APPENDIX C

OVERALL FLOW OF THE GENERATION PROCEDURE

This chart shows those routines in the CREATE3 program which are called when creating a SLP file.



APPENDIX D

COMMON BLOCKS ESSENTIAL TO THE GENERATION PROCEDURE

COMMON blocks used which transmit the data between the routines that create the SLP file:

CETBL1

CETBL3

CETBL4

CETBL9

CHEV

CONST

FILES

INPUT

SAVE

SLPOPT

SLPREC

SWITCH

TIMCOF

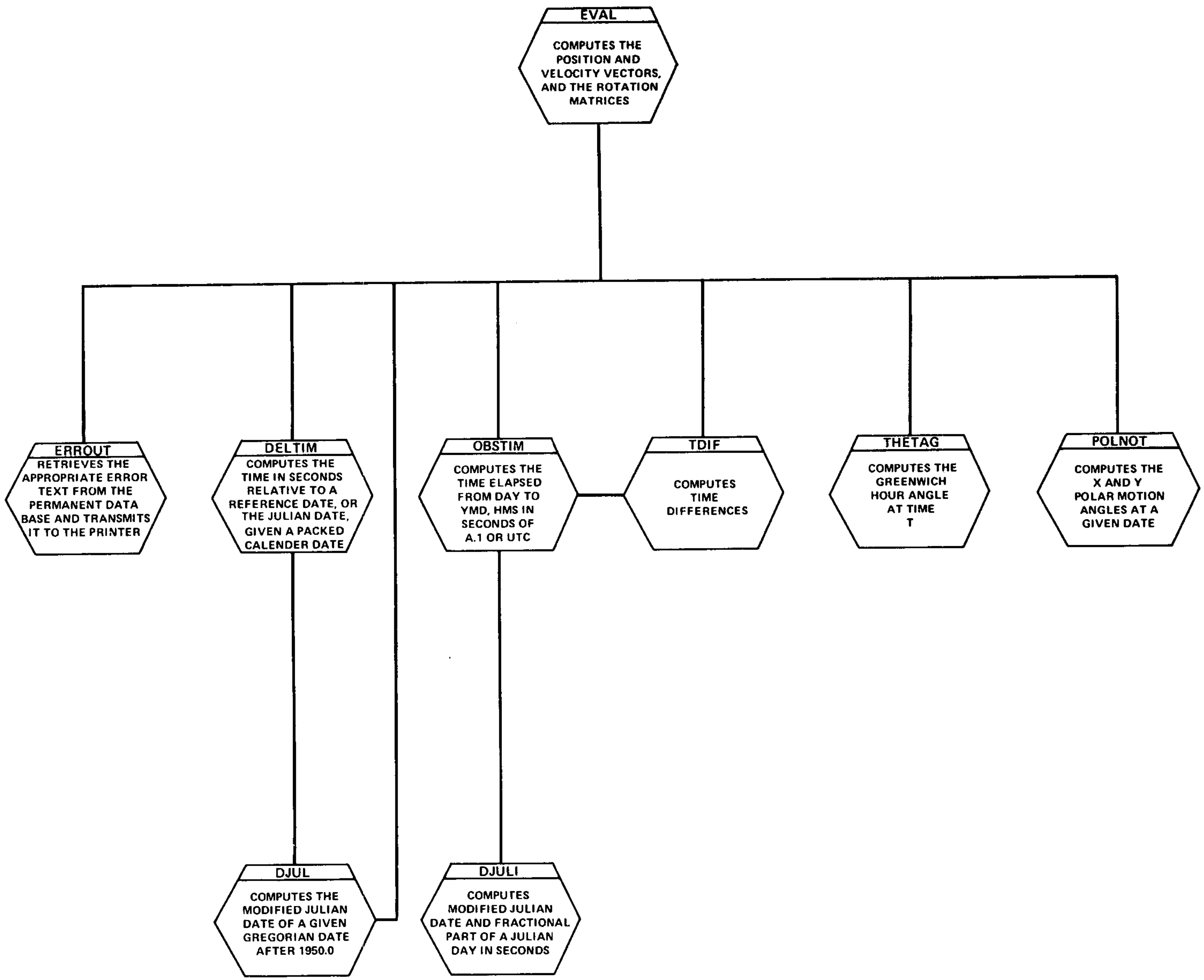
XLABEL

APPENDIX E

ABBREVIATED GTDS SYSTEM USAGE OF THE SLP FILE

The COMMON BLOCKS used by the routine EVAL and the routines called by EVAL which enable the data to be transmitted between the routines.

SUBROUTINE	COMMON BLOCKS
EVAL	CONST, FILES, FRC, SATPOS, SLPOPT, SLPREC, SWITCH
ERROUT	FILES, SWITCH
TDIF	TIMCOFF
POLMOT	TIMCOFF, SATPOS
THETAG	CONST, SATPOS, SLPOPT, SLPREC, SWITCH


EVAL
COMPUTES THE POSITION AND VELOCITY VECTORS, AND THE ROTATION MATRICES
ERROUT
RETRIEVES THE APPROPRIATE ERROR TEXT FROM THE PERMANENT DATA BASE AND TRANSMITS IT TO THE PRINTER
DELTIM
COMPUTES THE TIME IN SECONDS RELATIVE TO A REFERENCE DATE, OR THE JULIAN DATE, GIVEN A PACKED CALENDER DATE
OBSTIM
COMPUTES THE TIME ELAPSED FROM DAY TO YMD, HMS IN SECONDS OF A.1 OR UTC
TDIF
COMPUTES TIME DIFFERENCES
THETAG
COMPUTES THE GREENWICH HOUR ANGLE AT TIME T
POLNOT
COMPUTES THE X AND Y POLAR MOTION ANGLES AT A GIVEN DATE
DJUL
COMPUTES THE MODIFIED JULIAN DATE OF A GIVEN GREGORIAN DATE AFTER 1950.0
DJULI
COMPUTES MODIFIED JULIAN DATE AND FRACTIONAL PART OF A JULIAN DAY IN SECONDS

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